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# Spot clearing in energy markets considering exercise of interruptible load options by retailers

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## ABSTRACT

The retail customers enjoy pre-agreed fixed price and quantity contracts, whereas the retailers ought to secure their energy at volatile spot market clearing conditions. This exposes the retailers to volatility of price and quantity. As one of the ways to mitigate such risks, the retailers secure interruptible load options from their customers. The goal of these options is to give the retailers the flexibility to buy at the spot conditions or to exercise their interruptible load options, whichever is favourable. This paper proposes a mathematical formulation for spot clearing mechanism in energy markets that considers the exercise of interruptible load options by retailers. Spot clearing is formulated as a quadratic programming problem that considers the generators supply bids, customers and retailers demand bids to the whole sale electricity market and retailer contracts and interruptible loads options in the retail market to determine the market clearing price and quantities of all the market players. The proposed formulation is analysed on a 3 bus, 6 bus and 46 bus test system.

**Keywords:** Spot Clearing; Retail Market; Spot Market; Quadratic Programs; Active Set Method

**Abbreviations:**

| | |
|---|---|
| $I$ | Retailer Index |
| $J$ | Generator Index |
| $N$ | Customer Index |
| $G_{\mathrm{S}}^{j}$ | Total electricity sold by generator $j$ in spot market |
| $G_{\mathrm{R}}^{j}$ | Total electricity sold by generator $j$ in the retail market |
| $C_{j,i}$ | Electricity purchased by retailer $i$ from generator $j$ |
| $t_i$ | Load interrupted by retailer $i$ |
| $R_i$ | Total electricity purchased by retailer $i$ from the wholesale spot market |
| $D_S^n$ | Electricity purchased by customer $n$ from the spot market |
| $D_R^n$ | Electricity purchased by customer $n$ from the spot market |
| $D_i$ | Total electricity purchased by customers from retailer $i$ in the retail market |
| $\psi_i$ | Fixed price consumers are charged for purchase of electricity from retailer $i$ |
| $b_j$ | Intercept for generator j bid |
| $m_j$ | Slope for generator j bid |
| $\overline{C_{j,i}}$ | Maximum electricity that can be purchased from generator $j$ by retailer $i$ |
| $\overline{r_{j,i}}$ | Load curtailment of transaction between generator $j$, retailer $i$ |
| $\overline{G_j}$ | Maximum electricity generator $j$ is able to supply |

## 1. INTRODUCTION

In deregulated electricity market such as in Singapore, there exists wholesale markets and retail markets. In wholesale electricity market, every half an hour, generators bid to sell electricity and retailers and customers bid to purchase electricity. Retailers sell the electricity that they purchased in the whole sale spot market, to customers in the retail market. Customers have two choices i.e. they can choose to buy electricity from retailers under customised power plans from the retail market or from the whole sale electricity market at price that fluctuates every half an hour [1].

Spot market prices are highly volatile due to a number of reasons that include non-storability of electricity, time varying demand which is peak at certain hours, loss of generation due to maintenance or forced outage of generation etc. Consequently electricity market participants, especially the retailers, who purchase electricity in the wholesale market at spot price and sell to customers at pre-agreed fixed price are exposed to huge financial risks. To mitigate such risks, retailers can purchase interruptible load contracts from the customers so that they can choose to exercise the load interruption in case the spot price goes higher than the pre –agreed fixed price. The current literature for market operation can be broadly classified into load curtailment cost minimization as in [2,3]or electricity wholesale spot market operation cost minimization as in [4,5]. In this paper, we propose a mathematical formulation for spot clearing mechanism in energy markets that considers the exercise of interruptible load options by retailers. Spot clearing is formulated as a quadratic programming problem that considers the generators supply bids, customers and retailers demand bids to the whole sale electricity market and retailer contracts and interruptible loads options in the retail market to determine the market clearing price and quantities of all the market players. The proposed formulation is analysed on a 3 bus, 6 bus and 46 bus test system.

## 2. ELECTRICITY MARKET MODEL

An electricity market model consisting of *I* retailers, *J* generators and *N* customers is considered. For simplicity, it is assumed that each bus in the power system has either generator selling electricity or a customer purchasing electricity. The mathematical formulations for clearing electricity in the spot and retail market models are presented in this section.

### Generators

Generators sell power in the spot market by submitting linear upward slope bids to the market operator [4]. The linear bids can be represented as:

$$MC_i = b_i + m_i g_i \tag{1}$$

Total electricity sold by generator *j* to retailers and customers:

$$G_{\mathrm{R}}^{j} = \sum_{i=1}^{I} C_{j,i} \tag{2}$$

Total electricity sold by generator *j* to retailers in set *I*:

$$G_{\mathrm{T}}^{j} = G_{\mathrm{R}}^{j} + G_{\mathrm{S}}^{j} \tag{3}$$

### Customers

Customers purchase either from spot market at spot price or from retailers at pre-agreed fixed price ( $\psi$ ) and quantity (D).

Total demand bought by customer *n* from the spot market and retail market:

$$D_{\mathrm{T}}^{n} = D_{\mathrm{R}}^{n} + D_{\mathrm{S}}^{n} \tag{4}$$

Total demand bought by customer *n* from the retail market:

$$D_{\mathrm{R}}^{n} = \sum_{i=1}^{I} D_{n,i} \tag{5}$$

### Retailers

Retailers purchase from spot market at spot price and sell to its customers at pre-agreed fixed price ( $\psi$ ) and quantity (D). To mitigate risks, the retailers secure interruptible load options from their customers.

Total power bought by retailer *i* from the generators in set J in the spot market:

$$R_i = \sum_{j=1}^{J} C_{j,i} \qquad (6)$$

Total bilateral demand retailer $i$ has to supply in the retail market:

$$D_i = \sum_{n=1}^{N} D_{n,i} \qquad (7)$$

Retailers buy at the spot price if it cheaper than the fixed pre-agreed contract price and they exercise their interruptible load ( $t_i$ ) options if the spot price is expensive than the fixed pre-agreed contract price. So the pre-agreed fixed quantity contracts of retailer $i$ is met by either purchasing power from the spot market or by exercising their interruptible load options on its customers or a combination of both. Pre agreed contract quantity can be written as:

$$D_i = R_i + t_i \qquad (8)$$

**Spot Market Constraints**

It is assumed that there is sufficient generation to meet spot market demand. Also, Spot demand is inelastic to price. So the total power sold by generators in the spot market is equal to the total power bought by customers in the spot market:

$$\sum_{j=1}^{J} G_{\mathrm{S}}^{j} = \sum_{n=1}^{N} D_{\mathrm{S}}^{n} \qquad (9)$$

**Retail Market Constraints**

The pre-agreed fixed quantity contracts of retailers is met by either purchasing power from the spot market or by exercising the retailers interruptible loads options on its customers or a combination of both. It can be written as

$$\sum_{n=1}^{N} D_{\mathrm{R}}^{n} = \sum_{j=1}^{J} G_{\mathrm{R}}^{j} + \sum_{i=1}^{I} t_i \qquad (10)$$

## 3. PROBLEM FORMULATION

In this section, the mathematical formulation for spot clearing is presented. The optimal market clearing results would be to give the retailers the flexibility to buy at the spot conditions or to exercise their interruptible load options, whichever is favorable. The spot clearing formulation is set up as a quadratic programming optimisation problem with an objective to minimize the overall retailers cost, which is the sum of the cost of exercising interruptible load option on its customers and the cost of purchasing power from spot market, subject to generation limits, spot and retail market constraints. The overall market clearing formulation can be mathematically represented as:

$$min \quad z = \{\sum_{i=1}^{I} \psi_i t_i + \sum_{j=1}^{J} (b_j + m_j(G_{\mathrm{S}}^{j} + G_{\mathrm{R}}^{j}))(G_{\mathrm{S}}^{j} + G_{\mathrm{R}}^{j})\} \qquad (11)$$

**Subject to the following constraints:**

Spot market demand clearing:

$$\sum_{j=1}^{J} G_{\mathrm{S}}^{j} = \sum_{n=1}^{N} D_{\mathrm{S}}^{n} \qquad (12)$$

Total power provided by generator $j$ to retail market:

$$G_{\mathrm{R}}^{j} = \sum_{i=1}^{I} C_{j,i} \quad \forall j \in J \qquad (13)$$

Pre-agreed contracts for retailer $i$ is met by purchasing power from the spot market or by exercising the interruptible load options on its customers:

$$t_i + \sum_{j=1}^{J} C_{j,i} = D_i \quad \forall i \in I \qquad (14)$$

Spot market availability and load curtailment:

$$C_{j,i} - r_{j,i} = \overline{C_{j,i}} \quad \forall j \in J, \forall i \in I \qquad (15)$$

Generation Limit:

$$G_{\mathrm{S}}^{j} + G_{\mathrm{R}}^{j} \leq \overline{G}_j \quad \forall j \in J \qquad (16)$$

## 4. RESULTS

### A. 3 Bus System

The 3 bus test system was utilized to illustrate the proposed technique. The single line diagram of the test system is shown in [Fig 1]. The test system data and generator bid data are given in [5]. The test system is assumed to have two generators (G1, G2), two Retailers (R1, R2) and one customer (D1). The generators at buses 1 belong to G1, generators at buses 2 belong to G2. The loads at bus 3 belong to D1.The retailers R1 and R2 purchase electricity from G1 and G2 and sell the electricity to D1 at a fixed contract price in the retail market. R1 and R2 are both contracted to provide D1 with 200MW.Three sets of generator bids are given in Table 1 to analyse. The quadratic optimisation problem formed is solved with the active set method [8]. In scenario 1 [Table 2 - 4], the bid prices considered for generation in the wholesale spot market are low. This encourages retailers to purchase generation from the wholesale supply market at spot price. Majority of the generation that retailers are meant to provide to customers through bilateral contracts are purchased in the spot market at a lower spot price. Retailer 1 buys 200MW

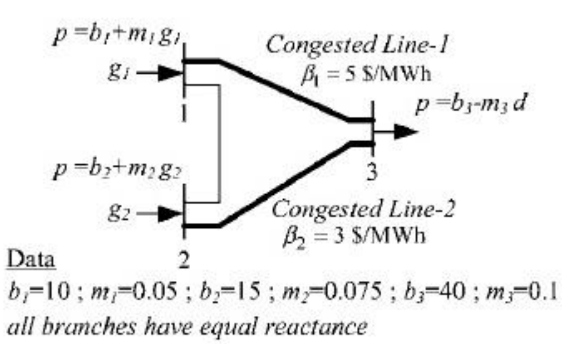
of power from generator 1 at a spot price of $22.50 while Retailer 2 buys 170MW of power from Generator 2 at a spot price of $27.50. The purchased power from the generators is used by retailers to satisfy their bilateral contracts with customers. 30MW of the bilateral contract between retailer 2 and the customer is unable to be fulfilled as Retailer 2 is not able to purchase it in the spot market at a spot price below the agreed market price. It therefore interrupts the load by 30MW. In scenario 2 [Table 5 - 7] the same bid prices of scenario 1 are considered. But retailers are only able to purchase 100MW of power from each generator. Retailers therefore increase their load interruption, to include the amount they would purchase from generators at a low spot price if not for the restrictions on purchase. Load interruption of retailer 1 and 2 therefore increases to 100MW each. In scenario 3 [Table 8, 9], a high spot market bid price is considered for the generators. This does not entice retailers to purchase power from either generator to satisfy their bilateral contract. The bilateral contracts between the retailers and customer are entirely interrupted.

**Table 1** Bid data

| Set 1-Scenario 1 | | | | Set 2-Scenario 2 | | | |
|---|---|---|---|---|---|---|---|
| Bid intercept | | Bid Slope | | Bid intercept | | Bid Slope | |
| G1 | G2 | G1 | G2 | G1 | G2 | G1 | G2 |
| 5 | 7 | 0.05 | 0.075 | 10 | 15 | 0.05 | 0.075 |

| Set 3-Scenario 3 | | | | | |
|---|---|---|---|---|---|
| Bid intercept | | Bid Slope | | Max transaction between generator and each retailer | |
| G1 | G2 | G1 | G2 | G1 | G2 |
| 5 | 7 | 0.05 | 0.075 | 100 | 100 |

**Figure 1**




***3 Bus-Scenario 1***

**Table 2** Retail market

| Name of Contract | Contract Quantity | Contract Price | Quantity Curtailed |
|---|---|---|---|
| R1-D1 | 200MW | $40/MW | 0MW |
| R2-D2 | 200MW | $40/MW | 30MW |

**Table 3** Spot market

| Generator | Spot Market Price ($/MW) | Generation used to clear spot market | Generation used to clear bilateral transactions |
|---|---|---|---|
| 1 | 22.5 | 150MW | 200MW |
| 2 | 27.5 | 50MW | 170MW |

**Table 4** Transactions between generators and retailers

| Generators / Retailer | 1 | 2 |
|---|---|---|
| 1 | 200MW | 0 |
| 2 | 0 | 170MW |
| Total generator produced by power | 200MW | 170MW |

***3 Bus – Scenario 2***

**Table 5** Retail market

| Name of Contract | Contract Quantity | Contract Price | Quantity Curtailed |
|---|---|---|---|
| R1-D1 | 200MW | $40/MW | 100MW |
| R2-D2 | 200MW | $40/MW | 130MW |

**Table 6** Spot market

| Generator | Spot Market Price ($/MW) | Generation used to clear spot market | Generation used to clear bilateral transactions |
|---|---|---|---|
| 1 | 22.5 | 150MW | 100MW |
| 2 | 27.5 | 50MW | 70MW |

**Table 7** Transactions between generators and retailers

| Retailer \ Generators | 1 | 2 |
|---|---|---|
| **1** | 100MW | 0 |
| **2** | 0 | 100MW |
| **Total generation produced by supplier** | 100MW | 100MW |

***3 Bus – Scenario 3***

**Table 8** Retail market

| Name of Contract | Contract Quantity | Contract Price | Quantity Curtailed |
|---|---|---|---|
| R1-D1 | 200MW | \$10/MW | 200MW |
| R2-D2 | 200MW | \$10/MW | 200MW |

**Table 9** Spot market

| Generator | Spot Market Price | Generation used to clear spot demand | Generation used to clear bilateral contracts |
|---|---|---|---|
| 1 | 11.4 | 128MW | 0MW |
| 2 | 12.4 | 72MW | 0MW |

**B. Graver 6 Bus System**

The Graver 6 bus test system was utilized to illustrate the proposed technique. The single line diagram of the test system is shown in Figure 2. The test system data and generator bid data are given in [5]. The test system is assumed to have three Generators (G1, G2 and G3), three Retailers (R1, R2, R3) and four customers (D1, D2, D3 and D4). The generator at bus 1 belongs to G1, generator at bus 3 belongs to G2 and generator at bus 6 belongs to G3. The loads at bus 1 belong to D1, at buses 2 to D2, at buses 4 to D3. The retailers R1, R2 and R3 purchase electricity from G1, G2 and G3 and sell the electricity to D1, D2, D3 and D4 at a fixed contract price in the retail market. R1, R2, R3 and R4 are contract to provide a total demand of 200MW each. Three sets of generator bids are given in [Table 10 and 11] to analyse. In [Table 12-14], just like in the 3 bus system, low bid prices are considered for the generators in the whole spot market. Generator 1 has the lowest bid price in the spot market with a bid intercept of 5 and bid slope of 0.010. Hence retailers 1 and 3 purchase a total power 305MW from generator 1. 200MW of which is bought by retailer 1 to fulfil its total contracted demand of 200MW. 105MW is bought by retailer 3 to fulfil a part of its contracted total demand of 200MW. Retailer 3 then purchases the remainder 95MW needed to fulfil its bilateral demands from generator 2.Retailer 2 also purchases 125MW of power from generator 2. Generator 3 provides power to clear customers' spot market demand of 200MW. Retailer 2 can therefore no longer purchase power from Generator 3 as the spot price exceeds its bilateral price. In scenario 2 [Table 15-17], the bid prices considered for all generators is high. Power from generators in the wholesale spot market is also used to clear spot market demand. By increasing generators' production further, generators' spot price is higher than bilateral price and retailers have no incentive to purchase power from the spot market. Therefore majority of the bilateral contract for retailers are interrupted. Total demand for retailer 1, 2 and 3 interrupted is 195MW, 113MW and 200MW respectively. For scenario 3 [Table 18 and 19], each retailer is only allowed to purchase 100MW of power from each generator, even though generators are able to provide more power at a spot price lower than the bilateral price. Retailers interrupt their load according to the amount of power they could purchase from the generators at a lower cost if not for restrictions on transactions.

**Figure 2**

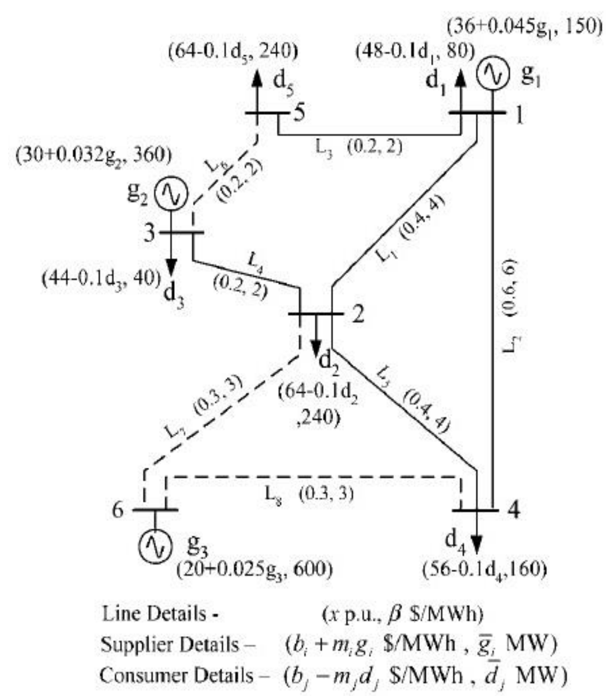



**Table 10** Bid data

| Set 1-Scenario 1 | | | | | |
|---|---|---|---|---|---|
| **Bid intercept** | | | **Bid slope** | | |
| G1 | G2 | G3 | G1 | G2 | G3 |
| 5 | 7 | 9 | 0.05 | 0.075 | 0.1 |

| Set 2-Scenario 2 | | | | | |
|---|---|---|---|---|---|
| Bid intercept | | | Bid slope | | |
| G1 | G2 | G3 | G1 | G2 | G3 |
| 10 | 15 | 20 | 0.05 | 0.075 | 0.1 |

**Table 11** Bid data

| Set 3-Scenario 3 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Bid Intercept | | | Bid Slope | | | Max transaction from generator to each retailer | | |
| G1 | G2 | G3 | G1 | G2 | G3 | G1 | G2 | G3 |
| 5 | 7 | 9 | 0.05 | 0.075 | 0.1 | 100 | 100 | 100 |

***6 Bus - Scenario 1***

**Table 12** Retail market

| Name of Contract | Contract Quantity | Contract Price | Quantity Curtailed |
|---|---|---|---|
| R1-D | 200MW | $40/MW | 0 |
| R2-D | 200MW | $40/MW | 75MW |
| R3-D | 200MW | $40/MW | 0 |

**Table 13** Spot market

| Generator | Spot Market Price | Generation used to clear spot demand | Generation used to clear bilateral transactions |
|---|---|---|---|
| 1 | 22.5 | 45 | 305 |
| 2 | 23.5 | 0 | 220 |
| 3 | 24.5 | 155 | 0 |

**Table 14** Transactions between generators and retailers

| Retailer \ Generator | 1 | 2 | 3 |
|---|---|---|---|
| 1 | 200MW | 0 | 0 |
| 2 | 0 | 125MW | 0 |
| 3 | 105MW | 95MW | 0 |
| Total generation produced by supplier | 305MW | 220MW | 0 |

***6 Bus - Scenario 2***

**Table 15** Retail market

| Name of Contract | Contract Quantity | Contract Price ($/MW) | Quantity Curtailed |
|---|---|---|---|
| R1-D | 200MW | 40 | 100 |
| R2-D | 200MW | 40 | 100 |
| R3-D | 200MW | 40 | 5 |

**Table 16** Spot market

| Generator | Spot Market Price | Generation used to clear spot demand | Generation used to clear bilateral transactions |
|---|---|---|---|
| 1 | 22.5 | 45 | 305 |
| 2 | 23.5 | 0 | 220 |
| 3 | 24.5 | 155 | 0 |

**Table 17** Transactions between generator and retailers

| Retailer \ Generator | 1 | 2 | 3 |
|---|---|---|---|
| **1** | 100MW | 0 | 0 |
| **2** | 0 | 100MW | 0 |
| **3** | 100MW | 95MW | 0 |
| **Total generation produced by supplier** | 200MW | 195MW | 0 |

***6 Bus – Scenario 3***

**Table 18** Retail market

| Name of Contract | Contract Quantity | Contract Price | Quantity Curtailed |
|---|---|---|---|
| R1-D | 200MW | $20/MW | 195 |
| R2-D | 200MW | $20/MW | 113 |
| R3-D | 200MW | $20/MW | 200 |

**Table 19** Spot market

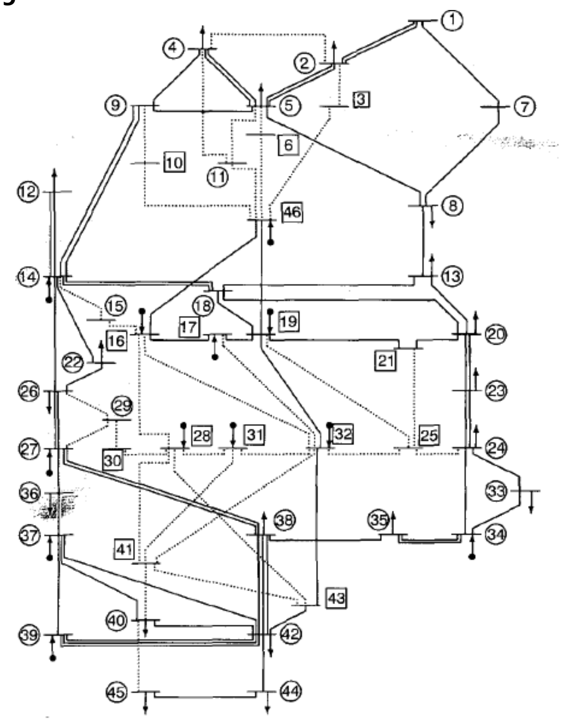
| Generator | Spot Market Price | Generation used to clear spot demand | Generation used to clear bilateral transactions |
|---|---|---|---|
| 1 | 12.5 | 145 | 5 |

| | | | |
|---|---|---|---|
| 2 | 13.5 | 0 | 86.67 |
| 3 | 14.5 | 55 | 0 |

**C. Brazilian 46 Bus System**

The Brazilian 46 test system was utilized to illustrate the proposed technique. The single line diagram of the test system is shown in Figure 3. The test system data and generator bid data are given in [6]. The test system is assumed to have 12 Generators, 12 Retailers and 4 customers. The retailers are each contracted to supply customers with 200MW of electricity. In scenario 1, retailers purchase this amount from generators since bid prices considered for the generators are low. In scenario 2, retailers aren't able to purchase electricity from the spot market due to generators' high bid prices. Therefore they interrupt the load. In scenario 3, limits are imposed on the amount of electricity generators can sell in the spot market. Retailers unable to purchase electricity from generators due to this, interrupt their load.

**Figure 3**



| Name of Contract | Contract Quantity | Contract Price | Quantity Curtailed |
|---|---|---|---|
| R1-D | 200MW | 80 | 0 |
| R2-D | 200MW | 80 | 100 |
| R4-D | 200MW | 80 | 35.13 |
| R8-D | 200MW | 80 | 100 |
| R9-D | 200MW | 80 | 100 |
| R11-D | 200MW | 80 | 200 |
| R12-D | 200MW | 80 | 43.74 |

***46 Bus Scenario 1***

**Table 20** Spot market

| Generator | 1 | 2 | 4 | 5 | 7 | 8 | 10 |
|---|---|---|---|---|---|---|---|
| Bilateral Transactions (MW) | 300 | 100 | 300 | 293.75 | 206.25 | 191.89 | 143.24 |
| Spot demand (MW) | 0 | 200 | 0 | 0 | 0 | 0 | 0 |
| Spot Price ($/MW) | 25 | 37.5 | 55 | 65 | 70 | 70 | 72 |

**Table 21** Retail market

| Name of Contract | Contract Quantity | Contract Price | Quantity Curtailed |
|---|---|---|---|
| **R1-D** | 200MW | 80 | 0 |
| **R2-D** | 200MW | 80 | 0 |
| **R4-D** | 200MW | 80 | 0 |
| **R8-D** | 200MW | 80 | 0 |
| **R9-D** | 200MW | 80 | 0 |
| **R11-D** | 200MW | 80 | 200MW |
| **R12-D** | 200MW | 80 | 0 |

***46 Bus Scenario 2***

**Table 22** Spot market

| Generator | 1 | 2 | 4 | 5 | 7 | 8 | 10 |
|---|---|---|---|---|---|---|---|
| Bilateral Transactions (MW) | 200 | 100 | 200 | 193.75 | 106.25 | 156.75 | 100 |
| Spot demand (MW) | 0 | 200 | 0 | 0 | 0 | 0 | 0 |
| Spot Price ($/MW) | 22 | 35.5 | 45 | 58 | 65 | 62 | 65 |

**Table 23** Retail market

| Name of Contract | Contract Quantity | Contract Price | Quantity Curtailed |
|---|---|---|---|
| R1-D | 200MW | 80 | 0 |
| R2-D | 200MW | 80 | 100 |
| R4-D | 200MW | 80 | 35.13 |
| R8-D | 200MW | 80 | 100 |
| R9-D | 200MW | 80 | 100 |
| R11-D | 200MW | 80 | 200 |
| R12-D | 200MW | 80 | 43.74 |

***46 Bus Scenario 3***

**Table 24** Spot market

| **Generator** | 1 | 2 | 4 | 5 | 7 | 8 | 10 |
|---|---|---|---|---|---|---|---|
| **Bilateral Transactions (MW)** | 300 | 0 | 50 | 0 | 0 | 0 | 0 |
| **Spot demand (MW)** | 0 | 162..38 | 0 | 26.73 | 0 | 0 | 0 |
| **Spot Price ($/MW)** | 25 | 27.17 | 32.5 | 35.346 | 0 | 0 | 0 |

**Table 25** Retail market

| **Name of Contract** | **Contract Quantity** | **Contract Price** | **Quantity Curtailed** |
|---|---|---|---|
| R1-D | 200MW | 40 | 0 |
| R2-D | 200MW | 40 | 200 |
| R4-D | 200MW | 40 | 200 |
| R8-D | 200MW | 40 | 200 |
| R9-D | 200MW | 40 | 200 |
| R11-D | 200MW | 40 | 200 |
| R12-D | 200MW | 40 | 0 |

## 5. CONCLUSIONS

Spot prices in Energy markets are highly volatile. As a result, market players are exposed to huge financial risks. It is therefore very important to consider risk mitigation strategies of market players. In this paper, we proposed a mathematical formulation for spot clearing mechanism in Energy markets that considers the exercise of interruptible load options by retailers. The proposed framework takes into account the risk mitigation strategy of the electricity market retailers. The proposed formulation can be further developed to facilitate more power system operation and planning studies considering the risk management of market players.

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